REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
Jan 2011		

4. TITLE AND SUBTITLE

Models and Computational Methods for Rarefied Flows
(Modèles et méthodes de calcul des écoulements de gaz raréfiés)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Research and Technology Organisation (NATO)
BP 25, F-92201 Neuilly-sur-Seine Cedex, France

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

RTO-EN-AVT-194

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public release, distribution unlimited.

13. SUPPLEMENTARY NOTES

Supporting documents are attached to the report as separate files (PDFfile). Papers presented during the AVT-194 RTO AVT/VK

14. ABSTRACT

The objectives of this Lecture Series were to review the up-to-date physico-chemical models that describe rarefied gas effects in flows in the transition and rarefied regimes. Furthermore, details of numerical simulation strategies were presented, including relevant applications. The course was tailored to provide professionals and students working and/or supporting industries, space agencies, and defense programs a snap shot of the state-of-the-art in this rapidly progressing field of research.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U	SAR	5	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-194)TP/410

www.rto.nato.int

RTO EDUCATIONAL NOTES **EN-AVT-194**

Models and Computational Methods for Rarefied Flows

(Modèles et méthodes de calcul des écoulements de gaz raréfiés)

Papers presented during the AVT-194 RTO AVT/VKI Lecture Series held at the von Karman Institute, Rhode St. Genèse, Belgium, 24 - 28 January 2011.

Published January 2011

Distribution and Availability on Back Cover

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

Published January 2011

ISBN 978-92-837-0129-3

Models and Computational Methods for Rarefied Flows

(RTO-EN-AVT-194)

Executive Summary

Rarefied gas effects are encountered in a variety of flow applications ranging from hypersonic flights at high altitude, ballute entry and descent during planetary missions, station-keeping and orbit transfer of satellites, to micro-scale gas flows, such as in Micro-Electro-Mechanical Systems (MEMS). The conventional fluid dynamics Navier-Stokes equations, based on a continuum assumption, fail to accurately describe rarefied gas effects. They can be investigated at microscopic level by means of stochastic methods, such as Direct Simulation Monte Carlo (DSMC), as well as by means of deterministic solvers for the Boltzmann equation. Macroscopic transport equations can also be developed based on moments of the Boltzmann equation for the transition between the rarefied and continuum regimes.

The objective of this RTO/VKI Lecture Series is to review the up-to-date physico-chemical models, experimental facilities, and numerical simulation strategies that describe rarefied gas effects in flows in the transition and rarefied regimes, including relevant aerospace applications. The series is tailored to provide professionals and students working and/or supporting industries, space agencies, and defense programs a snap shot of the state-of-the-art in this field of research. Prominent professors and scientists from seven countries representing sixteen institutions for a total of twenty lectures were invited to give classes on their field of expertise. A total of thirty students and professionals attended the course.

The five-day course covered lectures spanning fundamental theory and numerical methods to experiments and applications. After a thorough review of rarefied gas effects in hypersonics, the limits of validity of the hydrodynamic regime were given. Then, the lectures focused on the physico-chemical models and computational methods for kinetic equations. A presentation of the DSMC method was followed by more specialized topics such as hybrid particle-continuum numerical methods, programming on GPU, and deterministic Boltzmann solvers. The second part of the series dealt with continuum models based on high order moments of the Boltzmann equation. The regularized Grad closure model and their numerical solution method was presented with applications to microfluidic device flows. The fourth day was devoted to experimental data and facilities for both aerothermodynamics and electric propulsion. Finally, simulations in the field of electric propulsion, semi-conductors, and hypersonics concluded this series.

Modèles et méthodes de calcul des écoulements de gaz raréfiés

(RTO-EN-AVT-194)

Synthèse

Les effets des gaz raréfiés se rencontrent dans un ensemble d'applications variées qui vont des vols hypersoniques à haute altitude, de l'entrée et de la descente de ballutes lors des missions planétaires, du maintien à poste des stations orbitales et des transferts d'orbites de satellites, aux flux de gaz microscopiques, tels que les microsystèmes électromécaniques (MEMS). Les équations conventionnelles Navier-Stokes de dynamique des fluides, basées sur un continuum supposé, n'arrivent pas à décrire précisément les effets des gaz raréfiés. Ces effets peuvent être examinés au niveau microscopique par des méthodes stochastiques, comme la Simulation Directe Monte Carlo (DSMC), ainsi que par les résolveurs déterministes de l'équation de Boltzmann. Des équations de transport macroscopiques peuvent aussi être développées sur la base de moments de l'équation de Boltzmann, pour une transition entre les régimes raréfiés et de continuum.

L'objectif de cette série de conférences RTO/VKI est de passer en revue les modèles physico-chimiques actualisés, les installations expérimentales et les stratégies de simulation numérique qui décrivent les effets des gaz raréfiés dans les flux des régimes de transition et de raréfaction, et incluant les applications aérospatiales correspondantes. Cette série de conférences est conçue de façon à fournir aux professionnels et aux étudiants des industries et/ou du support industriel, des agences spatiales et des programmes de défense, un aperçu de l'état de l'art dans le domaine de la recherche. Pour un total de vingt conférences, des professeurs et des scientifiques éminents de sept pays représentant seize institutions ont été invités à donner des cours dans leurs domaines d'expertise. Au total, trente étudiants et professionnels ont assisté à cette session.

La session de cinq jours comprenait des conférences couvrant la théorie fondamentale, et les méthodes numériques destinées aux expérimentations et à leurs applications. Après une revue approfondie des effets des gaz raréfiés en hypersonique, on a déterminé les limites de validité du régime hydrodynamique. Puis, les conférences se sont concentrées sur les modèles physico-chimiques et sur les méthodes de calcul des équations cinétiques. Une présentation de la méthode DSMC a été suivie par des sujets plus spécialisés tels que les méthodes numériques de continuum-particules hybrides, la programmation en GPU et les résolveurs Boltzmann déterministes. La seconde partie de la série de conférences a traité des modèles de continuum basés sur les moments du premier ordre de l'équation de Boltzmann. Le modèle régularisé de fermeture de Grad et sa méthode de résolution numérique ont été présentés avec des applications sur les écoulements de dispositifs micro-fluidiques. Le quatrième jour a été dédié aux données et installations expérimentales concernant à la fois l'aérothermodynamique et la propulsion électrique. Enfin, des simulations dans le domaine de la propulsion électrique, des semi-conducteurs et de l'hypersonique ont conclu cette série de conférences.